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Effect of Polymer Quenchants on the Toughness and Hardness of Different Medium Carbon Low Alloy Steels

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Abstract

In the present study, medium carbon low alloy (MCLA) steels like AISI 5140 (EN18) and AISI 4140 (EN19) are treated in different quenching media under solutionizing temperature of 855°C. Quenched in SAE 250 oil, polyethylene glycol (PEG) (10% and 30%), and water. The quenched samples are step-tempered at 575°C and at 220°C sequentially with 60 minute soaking time. BHN, YS, UTS and tensile toughness are determined for the untreated and heat-treated samples. It is found that there is an excellent correlation, with correlation coefficients of 0.97. The standard generalized equation for these two steels are established. Tensile toughness = 19000 + 12 BHN- 215 El. The study revealed that the PEG is better in terms of cost, fire-resistant and biodegradable. 30% polymer quenched samples result in better tensile toughness properties as compared to 10% polymer quenched samples.

Keywords: *Medium carbon low alloy steel (MCLA), AISI 5140, AISI 4140, Polyethylene glycol (PEG), Tensile toughness, Percentage elongation.*

1.0 Introduction

Engineers have often encountered Medium carbon low alloy (MCLA) steel failures in industrial applications. Failures not only result in fracture, but also imply a decrease in performance of parts. When failure occurs, consultation with a materials specialist is an essential first step in the troubleshooting process. By virtue of his knowledge of materials, the materials specialist can help the engineer by defining the problem, identify possible causes, and determine what type of information is needed to verify or refute each possible cause. So it is very important for engineers and materials scientists for the characterization of material, i.e., to study the metallurgical variables such as alloy composition, heat treatment and microstructure, to suggest the complementary or alternative techniques that will yield supplemental or more useful information. Therefore, heat treatment is one of the solutions to improve mechanical properties and to minimize failures [1].

MCLA steels like EN18 (AISI 5140) and EN19 (AISI 4140) have found widespread applications in the aerospace, automotive, marine, railways, agricultural, structural engineering and power industries. The heat treatment of these steels offers enhanced strength and toughness for specific applications. Traditionally, water and oil are used as the quenching media for the heat-treated steel parts. To overcome the drawbacks of the traditional quenchants; modern synthetic quenchants like polyethylene glycol (PEG), polyalkalyne glycol (PAG) are generally used. The present investigation deals with the effect of PEG on the mechanical property of the selected MCLA steels under forging industry environment [2].

Heat treatment is the technique of achieving changes in mechanical characteristics in practice. It is primarily determined by microstructural transformations, which occur under various heat treatment circumstances with differing holding times and tempering temperatures. The applications where heat treated components can be employed with the environmental conditions are determined by the final end structure of the heat treated components [3].

1.1 Standard Heat Treatment Procedures for EN Steels

Heat treatment is generally carried out as per customer specifications in batch type furnaces. Clear uniform ferrite-pearlite distribution is ensured after normalizing and taken care to avoid the presence of the low temperature transformation product. Desirable tempered martensite structure with a permissible percentage of binate is ensured by direct hardening the carbon and alloy steels [4,5]. The summary of heat treatment of EN steels and soaking time are shown in Tables 1 and 2 [6].

Table 1: Summary of heat treatment for en steels [6]

	Process	Heat Treatment Temperature, ºC	
		EN18	EN19
1	Normalizing	845-900	845-900
2	Hardening	830-870	830-870
3	Tempering	175-220	175-230

Table 2: Soaking time for various heat treatments [6]

	Process	Time in Minutes/25 mm of section
1	Normalizing	25 - 50
2	Hardening	25 - 40
3	Tempering	50 - 75

1.2 Why Polymer Quenchants Preferred in MCLA steels

Ability of quenching medium to extract heat from hardened sample expressed in terms of the h value, quench severity = h/2k, where, h = heat transfer coefficient and k = thermal conductivity. Water quenching is faster than oil quenching due to:

1. Specific heat of water is higher than most regular oils.
2. Lower viscosity of water compared to oils.
3. Density of water is higher than that of oil.

Thus water has a higher convection co-efficient as compared to oils (for removal of heat from the hot material) thus water has a better quench efficiency. Oil quenching is less drastic than water quenching and hence produces less distortion. Polymer solutions are environment friendly and biodegradable. The cooling rates achieved by polymer quenchants are faster than water due to their accelerated wetting. Higher concentration of polymer provides the slower cooling rate due to the formation of the thicker coating on the surface of quenching by [7,8];

1. Controlling quenching speed
2. Distortion control
3. Control of residual stress

Also, the polymer provides a unique mechanism for controlling the heat transfer from the hot metal by surrounding the metal piece with polymer rich coating. Non-uniform quenching may result of agitation is not used because of localized hot spots resulting from uneven heat removal from the metal surface. This may lead to spotty hardness, increased surface cracking, distortion and higher residual stress. Therefore, agitation is an important parameter in polymer quenching applications, both to ensure a uniform polymer film around a quench part and to provide a uniform heat extraction from the hot part to the adjacent area of quenchants by preventing a buildup of heat in the quench region. The typical process variables for various quenchants are shown in Table 3. With the increase in polymer concentration and bath temperature the cooling rate can be reduced to such an extent that many metals do not transform to martensite at all, but form binate or fine pearlite [9,10].

Table 3: Process variables and cost of various quenchants [10]

	Process	Variable	Quench severity	Cost in Rupees
01	Water	No agitation	1.0	0.2/litre
02	Oil	No agitation	0.25-0.30	300/litre
03	Polymer	Good agitation	0.6	340/litre

2. Experimental Details

2.1 Forging

The forging temperature and the amount of hot work are the two most important parameters for ensuring uniformity of structure and mechanical properties of the component after heat treatment. It is therefore essential that the forgings are never over-heated. Adequate care is taken to forge the components within the prescribed temperature range of 850–1100^{0}C. MCLA steels, viz., EN18 and EN19 were forged in the Vishnu Forging Industries Ltd, Bangalore. Figure 1 shows the forging procedure of selected steels by power hammer in forging shop [14,15].

Forgings are all dimensionally checked and are routinely normalized and tempered unless otherwise specified. Forgings are generally rough machined with allowances before dispatch. Die forgings are shot blasted. It is ensured that forgings are free from defects such as cracks, flakes, seams, segregation with a reduction ratio of 30%- 40%.

2.2 Test Samples Preparation

The heat treated forged steel rods were taken to the workshop for machining operations. A set of each steel sample was prepared from the rod of 20 mm diameter for hardness, tensile, impact, fatigue, machinability and microstructural analysis. Table 4 indicates the standards used for the current study.

The quenchants used in the study are oil (SAE 250 gear oil), 10% polymer solution (PEG), 30% polymer solution (PEG) and water. The tensile tests are conducted to evaluate the mechanical properties of selected MCLA steels.

Table 4: General test standards used in this study

	Tests carried	Standard used
1	Brinell Test	ASTM 92
2	Tensile Test	ASTM E-8

Figure 1: Forging of selected steels by power hammer in forging shop

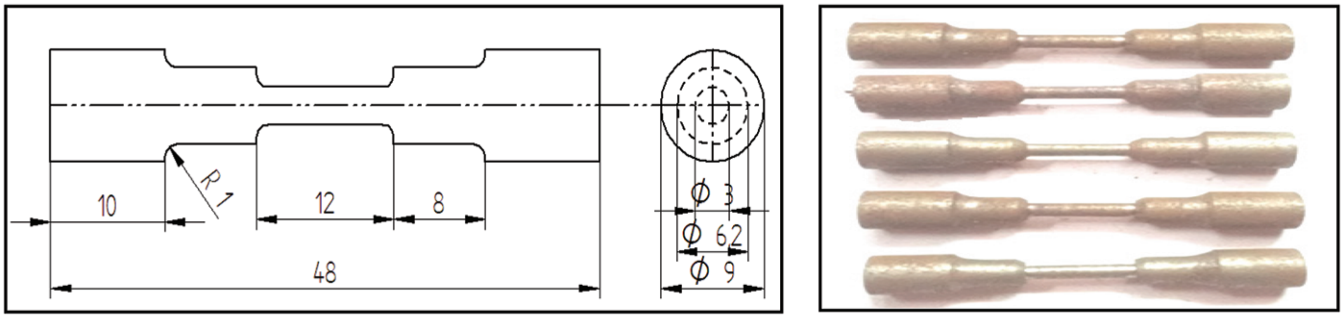

Figure 2: Geometry and tensile test samples

The tensile strengths of the untreated and heat treated samples were determined using Hounsfield Tensometer according to ASTM E8 standard. This standard specifies that the gauge lengths for most of the round samples are required to be 4d, where d is the diameter of the sample. The maximum tensile load which the tensometer can bear is 2000 kg or 19620 N. It is electrically operated and interfaced with the computer for observing the results. Figure 2 shows the geometry and photographs of the samples tested.

2.3 Tensile tests for EN18

The measured values of yield strength (YS), tensile strength, tensile toughness, % elongation and % reduction in area for untreated and heat treated samples of EN18 steels are tabulated in Table 5 whereas Table 6 shows the tensile toughness values of untreated and heat-treated for EN18. It was also observed that all the tensile failures were cup-and-cone fractures.

Figure 4 shows the variation of hardness and ultimate strength for the EN18 steel samples when the quenchants is changed from oil to polymer and then to water. It is clear that water and polymer quenching result in a significant increase in hardness and UTS, followed by oil quenching; forged samples have the lowest BHN and UTS. Quenching in water and polymer increases hardness by 57% and 52%, UTS by 29% and 27% respectively as compared to forged samples.

Table 5: BHN of Untreated and Heat-Treated for EN18

	Sample quenching medium	Tempering Temperature (°C)	BHN
1	Forged	-	172
2	Oil	575, 220	242
3	10 % Polymer	575, 220	250
4	30 % Polymer	575, 220	262
5	Water	575, 220	270

Figure 3: Tensile tested samples and Results

Figure 5 shows the variation in YS and UTS for the EN18 steel samples when the quenchant is changed from oil to polymer and then to water. It is clear that water and polymer quenching have a significant increase in YS and UTS followed by oil quenching; forged samples have the lowest YS and UTS. Quenching of steel samples in water and polymer, increases YS by 31% and 28%, and UTS by 29% and 26% respectively as compared to forged samples.

To understand the interrelationship between mechanical properties of EN18, a plot of BHN versus UTS for EN18 steel

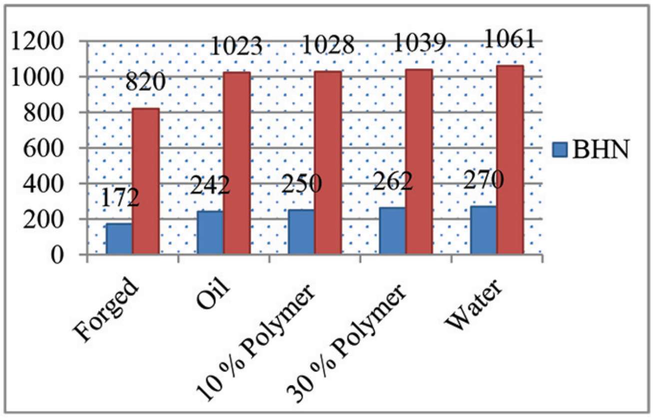

Figure 4: Variation in BHN and UTS for EN18

Table 6: Tensile toughness of Untreated and Heat-Treated for EN18

	Sample Quenching Medium	Tempering Temperature (°C)	Yield Strength (MPa)	Tensile Strength (MPa)	Tensile Toughness (N/m^2)	EL %	RA %
1	Forged	-	656	820	13575	35.2	68
2	Oil	575, 220	821	1023	16002	29.5	62.8
3	10 % Polymer	575, 220	824	1028	16018	29	59.8
4	30 % Polymer	575, 220	841	1039	16044	28.8	57.5
5	Water	575, 220	860	1061	16057	28.2	57.2

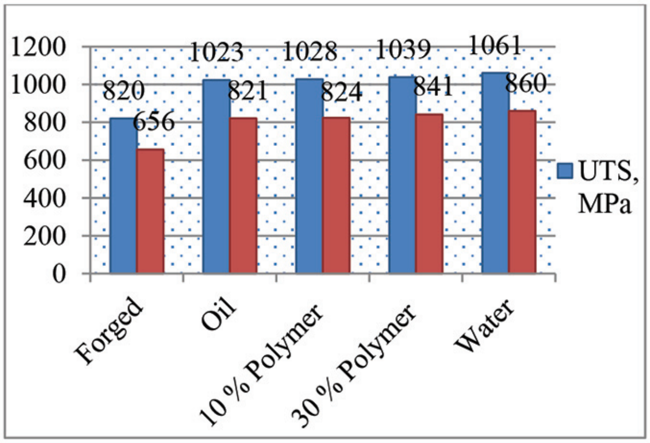

Figure 5: Variation in YS and UTS for EN18

was drawn as shown in Figure 6. It was found that there was excellent correlation between the two mechanical properties, with correlation coefficient of 0.99. Similar correlation was made between BHN and tensile toughness for EN18 steel as shown in Figure 7. The correlation was highly significant, with correlation coefficient of 0.97.

The measured values of variation in % elongation and % reduction in area for EN18 steel samples are shown in Figure 10. It is clear that water and polymer quenching decreases % elongation by 24% and 22%, % reduction in area by 18% as compared to forged samples.

It is clear from Figures 4, 5 and 10 that while the BHN, YS and UTS values are enhanced by increasing the severity of quench, the ductile properties like % elongation and % reduction in area are decreased by increasing the severity of quench.

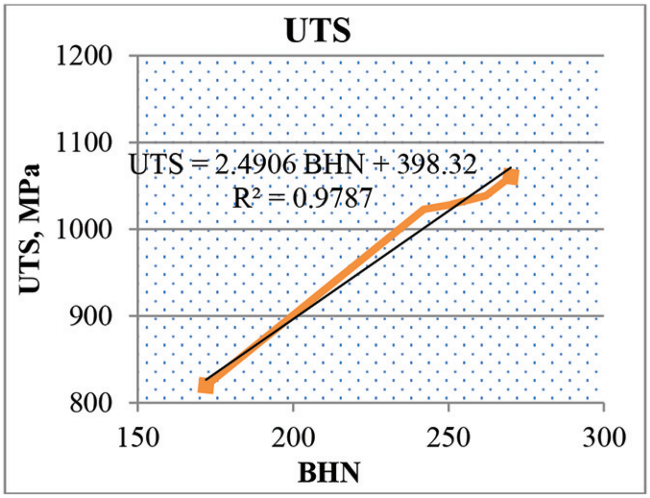

Figure 6: Variation in BHN and UTS for EN18

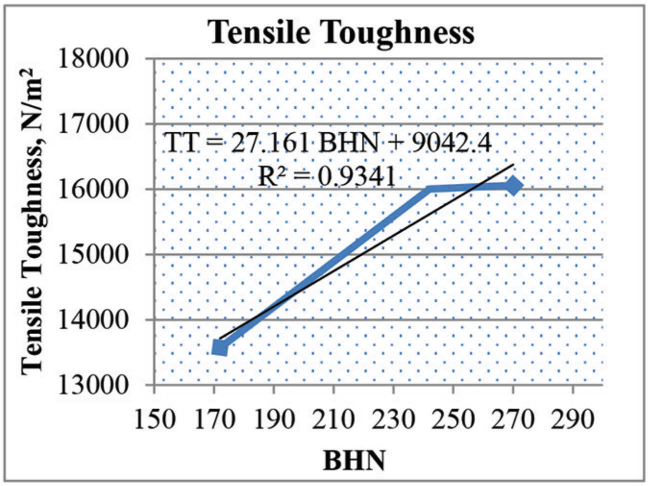

Figure 7: Variation in BHN and TT for EN18

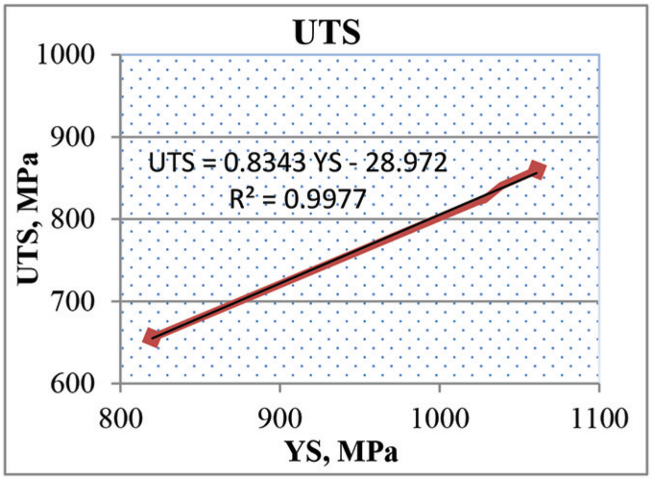

Figure 8: Variation in YS and UTS for EN18

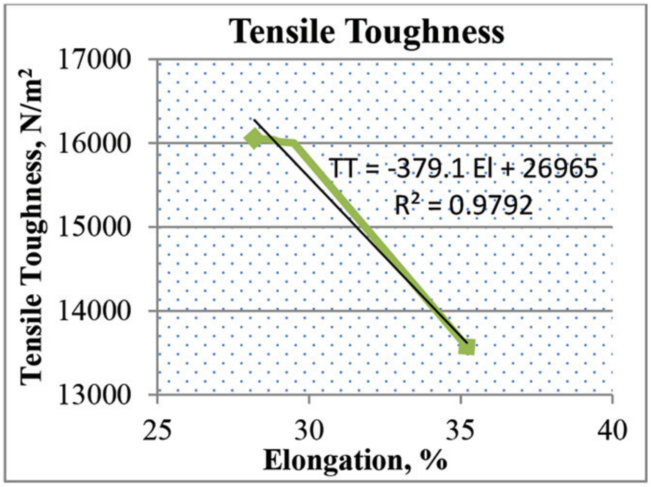

Figure 9: Variation in El and TT for EN18

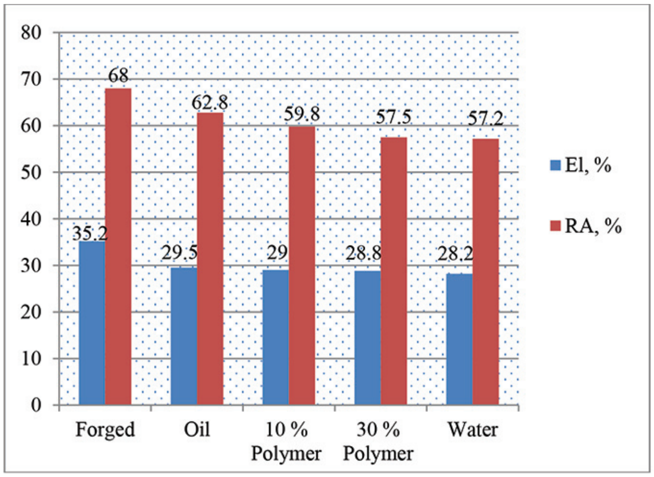

Figure 10: Variation in El and RA for EN18

Observations

1. The hardness of the EN18 steel increases with different quenching media, quenching in water having the maximum impact on hardness (270 BHN) followed by polymer quenching (262 BHN), oil quenching (242 BHN) and forged samples (172 BHN) have the least effects.
2. The YS and UTS of the EN18 steel increases with different quenching media and in step; tempered condition. Quenching in water has the maximum impact on tensile strength (1061 MPa) followed by polymer quenching (1039 MPa), oil quenching (1023 MPa) and forged samples (820 MPa) have the least effect.
3. The plot of UTS versus YS for EN18 steel is shown in Figure 8 and a plot of tensile toughness versus % elongation is shown in Figure 9. From the correlation coefficients (0.999, 0.99), it is found that UTS and YS as well as tensile toughness and % percentage elongation are excellently correlated.

2.5 Tensile Tests for EN19

The measured values of BHN for EN19 steel for untreated and heat treated samples of EN19 steels are tabulated in Table 7.

The measured values of YS, UTS, tensile toughness, % elongation and % reduction in area for EN19 are tabulated in Table 8.

The values (Tables 7 and 8) were compared to untreated and heat treated values are fitted into bar chart as shown in Figure 11. This shows the variation of hardness and ultimate strength for the EN19 steel samples when the quenchant is changed from oil to polymer and then to water. It is clear that water and polymer quenching result in a significant increase in hardness and UTS, followed by oil quenching; forged

Table 7: BHN of Untreated and Heat-Treated for EN19

	Sample Quenching Medium	Tempering Temperature (°C)	BHN
1	Forged	-	180
2	Oil	575, 220	260
3	10 % Polymer	575, 220	272
4	30 % Polymer	575, 220	292
5	Water	575, 220	298

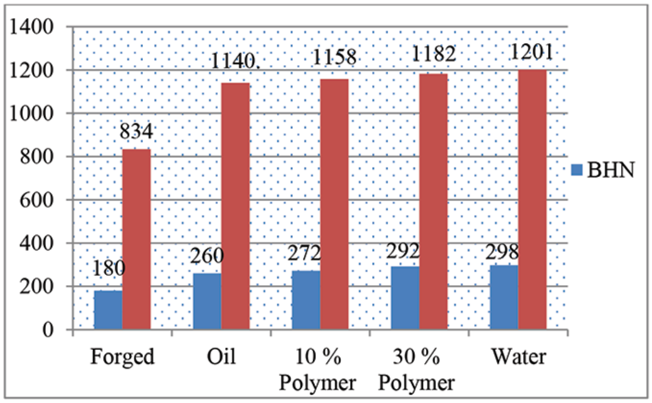

Figure 11: Variation in BHN and UTS of EN19

Table 8: Tensile Properties of Untreated and Heat-Treated for EN19

	Sample Quenching Medium	Tempering Temperature (°C)	Yield Strength (MPa)	Tensile Strength (MPa)	Tensile Toughness (N/m^2)	EL%	RA%
1	Forged	-	674	834	13968	34	62
2	Oil	575, 220	940	1140	16694	29.5	59
3	10 % Polymer	575, 220	948	1158	16723	28.5	56.9
4	30 % Polymer	575, 220	987	1182	16950	28.4	56.2
5	Water	575, 220	1006	1202	17180	27	56.6

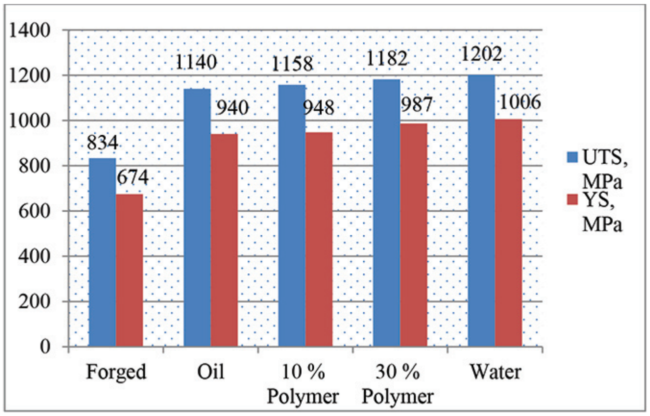

Figure 12: Variation of YS and UTS for EN19

samples have the lowest BHN and UTS. Quenching in water and polymer increases hardness by 66% and 62%, UTS by 44% and 42% respectively as compared to forged samples.

The YS and UTS values (Table 8) are compared to untreated and heat treated values are fitted into a bar chart as shown in Figure 12. This shows the variation in YS and UTS for the EN19 steel samples when the quenchant is changed from oil to polymer and then to water. It is clear that water and polymer quenching have a significant increase in YS and UTS followed by oil quenching; forged samples have the lowest YS and UTS. Quenching of steel samples in water and polymer, increases YS by 44% and 42%, and UTS by 49% and 46% respectively as compared to forged samples.

To understand the interrelationship between mechanical properties of EN19, a plot of BHN vs. UTS for EN19 steel was drawn as shown in Figure 13. It was found that there was excellent correlation between the two mechanical properties,

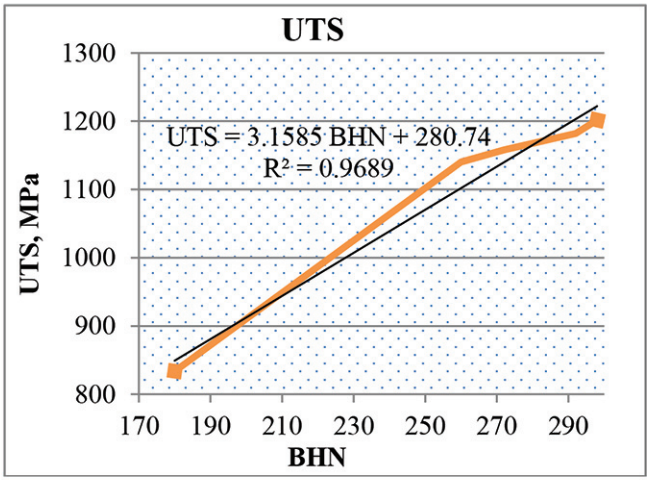

Figure 13: Variation in BHN and UTS for EN19

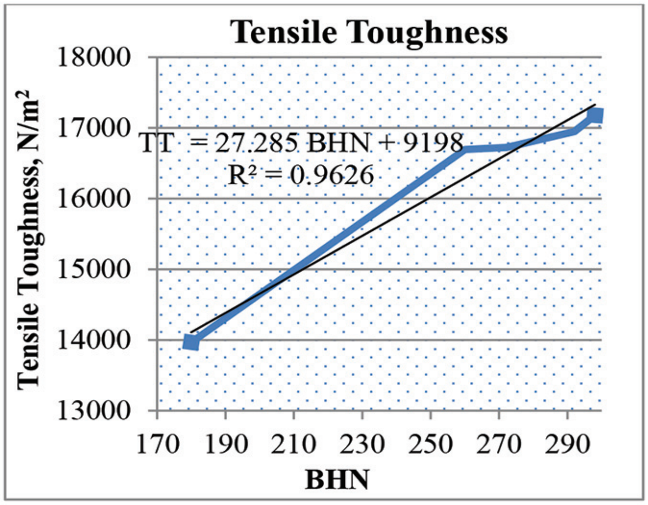

Figure 14: Variation in BHN and TT for EN19

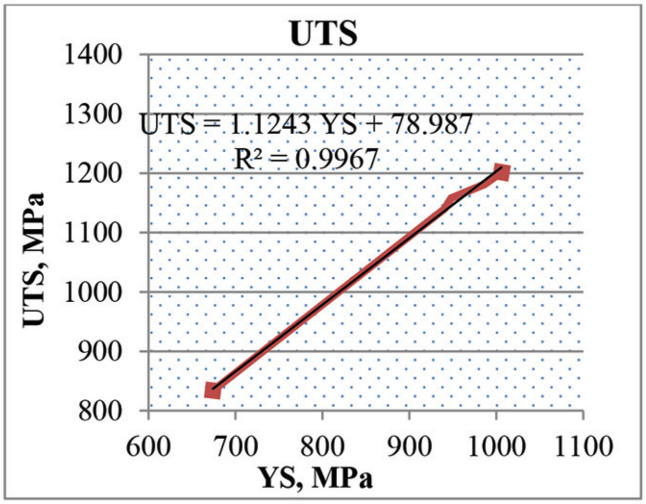

Figure 15: Variation in YS and UTS for EN19

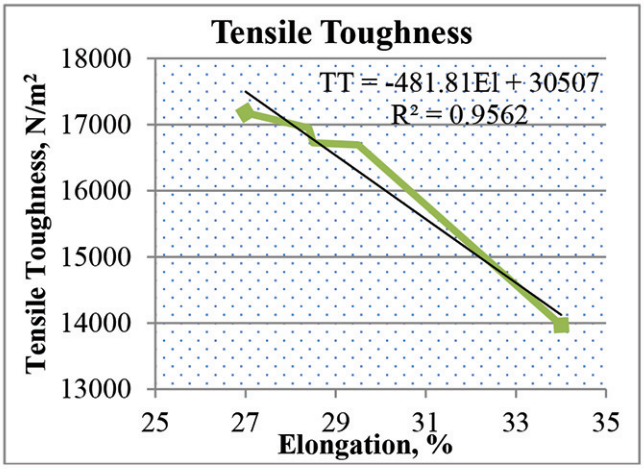

Figure 16: Variation in El and TT for EN19

with correlation coefficient of 0.98. Similar correlation was made between BHN and tensile toughness for EN19 steel as shown in Figure 14. The correlation was highly significant, with correlation coefficient of 0.98.

The measured values of variation in % elongation and % reduction in the area for EN19 steel samples are shown in Figure 17. It is clear that water and polymer quenching decreases % elongation by 24% and 22%, % reduction in area by 18% as compared to forged samples.

It is clear from Figures 11, 12 and 17 that while the BHN, YS and UTS values are enhanced by increasing the severity of quench, the ductile properties like % elongation and % reduction in the area are decreased by increasing the severity of quench.

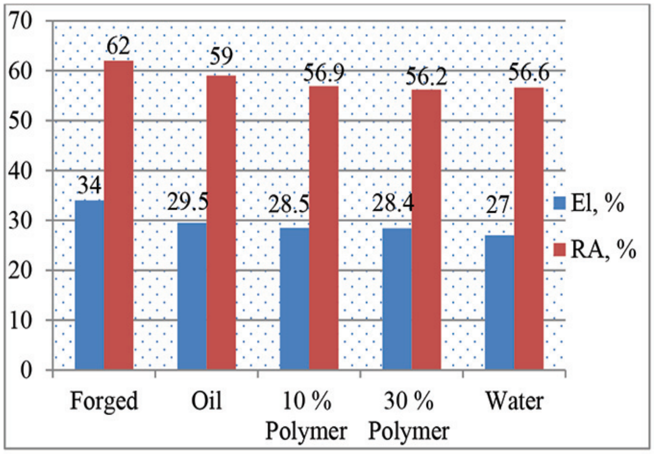

Figure 17: Variation of El and RA for EN19

Observations

1. The hardness of the EN19 steel increases with different quenching media, quenching in water having the maximum impact on hardness (298 BHN) followed by polymer quenching (292 BHN), oil quenching (260 BHN) and forged samples (180 BHN) have the least effects.
2. The YS and UTS of the EN19 steel increases with different quenching media and in step; tempered condition. Quenching in water has the maximum impact on tensile strength (1202 MPa) followed by polymer quenching (1182 MPa), oil quenching (1140 MPa) and forged samples (834 MPa) have the least effect.
3. The plot of UTS versus YS for EN19 steel is shown in Figure 15, and a plot of tensile toughness versus % elongation is shown in Figure 16. From the correlation coefficients (0.999, 0.99). It is found that UTS and YS as well as tensile toughness and % percentage elongation are excellently correlated.

3.0 Conclusions

1. It has been established that polyethylene glycol and water can be used as a quenching medium for MCLA forged steels.
2. The study has shown that using oil, water and polyethylene glycol as quenchants improves the mechanical properties compared to untreated steels.
3. The polyethylene glycol, can act as substitute for various quenchants without compromising on cost, quality and performance of the product.
4. Polyethylene glycol is better in terms of cost savings, is fire-resistant and biodegradable and has no negative impact on environmental conditions, especially during disposal activities, as compared to oils.
5. The 30% polymer quenched samples result in better mechanical properties as compared to 10% polymer quenched samples, i.e. higher concentration of polymer results better mechanical properties.
6. It is clear that the maximum tensile strength for EN18 and EN19 samples are obtained by water quenching in general followed by polymer quenching, oil quenching;
7. The measured values of BHN, elongation and tensile toughness were correlated in evaluating the standard tensile toughness equation for the two steels and shown in Table 9.
8. It was found that there was excellent correlation, with correlation coefficients of 0.97 for which are very significant, the standard generalized equation for all the four steels was found to be, Tensile toughness = 19000 + 13 BHN- 215 El.

Table 9: Tensile Toughness Equations for MCLA Steels

	Steel/Grades	Equation
1	EN18	TT= 18000 + 13 BHN – 185 El
2	EN19	TT= 19850 + 13 BHN – 240 El

4.0 Acknowledgement

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